91602
new 82-10

ontario hydro
research division

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

To: Mr. J. L. Bender
Manager, Transmission Stations Programs
Design and Development Division - Transmission

CAMBRIDGE PRESTON TS - GROUNDING SYSTEM STUDIES

R.P. Pillai

Soil resistivity tests were conducted at Cambridge Preston TS and the results indicated a complex multi-layer soil structure at the station. The measured soil resistivity is consistent with the geology at the site which is reported to be an abandoned gravel pit. Detailed modelling was performed to evaluate the adequacy of the grounding system performance at the station. For an ultimate HV fault current of 8.5 kA, the station ground potential rise and touch and step voltages are all found to be within the allowable limits. Simplified calculations indicated that the maximum station ground potential rise in the event of a LV ground fault would be well under the safe limit.

1.0 INTRODUCTION

Cambridge Preston TS is a new 230-kV station located at the corner of HWY 401 and HWY 24 in the city of Cambridge. The two transformers at the station are rated 75/125 MVA, 215.5/28 kV, Y_g/Z_{rg}, where, rg means reactor-grounded. The transformers are supplied from Galt TS via 230-kV circuits M20D and M21D. The station supplies loads through six 27.6-kV distribution feeders installed in underground ducts inside the station and then carried on poles outside the station. The cable shields/concentric neutrals are grounded only at the poles and separate copper neutral conductors of size 107 mm^2 (AWG 4/0) are used to connect the distribution neutrals to the station ground grid. The distribution neutrals are normally grounded at the distribution transformer taps. The station site is reported to be an abandoned gravel pit where soil is highly non-uniform with a gravel bed and high water table. Soil resistivity measurements were performed at the station since the electrical resistivities interpreted by others from previous measurements by P&C did not agree with each other. Detailed modelling was done to evaluate the grounding system performance at the station. The project was requested and funded by Design & Development Division - Transmission.

job	file	date	report no.
18-240-433	813.521	August 18, 1989	89-190-K

LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

2.0 SOIL RESISTIVITY MEASUREMENTS

2.1 Test Procedure

Soil resistivity surveys using the Wenner method/1/ were conducted near the station on May 13 and June 24, 1988 and on January 16, 1989. A Megger DET-2 ground resistance tester was used for this purpose. The survey locations are shown in Figure 1 and were limited in distance due to the station construction, access roads and highways. The site was characterized by coarse gravel from the surface to an unknown depth. High probe resistances and difficulty in driving the ground rods in the gravel were experienced during the tests. Water was used to reduce the probe resistance. Only one survey was successfully completed on May 13, 1988 due to the rain and subsequent instrument failure and therefore, the tests were repeated on June 24, 1988. The measurements on January 16, 1989 were aimed at determining the seasonal variations in the soil resistivity. However, heavy snowfall, high probe resistances of the frozen soil (gravel bed) and difficulty in driving the ground rods in the snow-covered gravel bed prevented us from obtaining representative data.

2.2 Measured Soil Resistivity

The apparent soil resistivities calculated from the measured Wenner data (equation 7.1 of the Grounding Guide /1/) are given in Table 1. The weather on the test date of May 13, 1988 was cloudy with heavy rain and thunderstorm in the morning and light rain in the afternoon and the surface gravel had water ponded. The weather on the test date of June 24, 1988 was sunny and warm and the surface condition was dry gravel. On the test date of January 16, 1989, the weather was very cold with snowfall and the gravel bed was covered with several inches of dry snow.

TABLE 1

CAMBRIDGE PRESTON TS
MEASURED APPARENT SOIL RESISTIVITIES

Probe Spacing (m)	Apparent Resistivities (Ω.m) Survey 1	Survey 2	Survey 3	Survey 4	Survey 5
1	1312	1798	1577	319	384
2	2066	2102	1575	538	447
5	1150	1364	479	575	488
10	468	440	453	434	373
20	692	650	798	587	696
50	1218	1184	1451	899	943
100	-	867	1464	503	-
Test Date (y-m)	88-05	88-06	88-06	88-06	89-01

2.3 Interpretation of Measured Resistivity Data

The measured apparent soil resistivities (Table 1) indicate a complex multi-layer (three or more layers) soil structure at the station. A two-layer soil model, an upper layer of resistivity ρ_1, thickness d and a second layer resistivity ρ_2 of infinite depth, is often considered adequate for grounding system studies. Therefore, attempts were made to fit a two-layer soil model to the measured data using the method given in Appendix D of the Grounding Guide /1/. The station ground resistance depends on grounding conductor spacings which normally range from the mesh

size to the largest diagonal dimension of the ground grid. Therefore, the model was approximately fitted to the data points at larger probe spacings (10 m and above) for use in station ground resistance calculations. The lower measured apparent resistivities at 100 m probe spacing may be due to water table, nearby fences or other metallic objects and therefore, were ignored for a conservative interpretation of the data. Table 2 compares the two-layer model parameters for all the surveys.

TABLE 2

CAMBRIDGE PRESTON TS
FITTED TWO-LAYER MODEL PARAMETERS FROM WENNER DATA

Survey	ϱ_1 (Ω.m)	d (m)	ϱ_2 (Ω.m)
1	300	8	2100
2	350	10	2100
3	260	7	2600
4	320	7	1120
5	470	11	1175
Global Fitting to Surveys 1, 2 & 3	350	10	2100

Surveys 4 and 5 were conducted along a bank (approximately 4-5 m high) on the west side of Hwy 24. Here, the lower measured results compared to the other locations may be due to the native soil, fill, nearby fences or other metallic objects in the vicinity. Therefore, surveys 4 & 5 were neglected in deriving a representative soil model for station grounding system calculations. Thus, as an alternate way of interpretation, the data points from surveys 1, 2 and 3 were plotted on the same graph and a two-layer model for station ground resistance was approximately fitted eliminating any scattered points. This two-layer interpretation yielded an upper layer resistivity of 350 Ω.m, thickness 10 m and a bottom layer resistivity of 2100 Ω.m and Table 2 compares this global model with the models from each survey. Figure 2 shows the plots of the field data and the globally fitted two-layer model curve.

Soil resistivity measurements were previously performed at the station site by P&C in 1987 /2/ and a two-layer interpretation of the data yielded an upper layer of 320 Ω.m, thickness 4 m and a bottom layer of 4160 Ω.m. Here also, the model was approximately fitted to the data points at larger probe spacings (10 - 100 m) for use in station ground resistance calculations as explained above.

Station touch and step voltages are normally sensitive to the soil resistivities at depths of grid burial to few meters below. Therefore, a sub-surface layer resistivity of 1800 Ω.m was derived as an average of the measured apparent resistivities at probe spacings 1 to 2 m from surveys 1, 2 and 3 (Table 1), for use in station touch and step voltage calculations.

3.0 MODELLED STATION GROUNDING SYSTEM PERFORMANCE

Appendix A summarizes the formulas used in the calculations, other than those given in the references.

3.1 Soil Resistivity

An equivalent soil resistivity of 840 Ω.m was derived for an estimated station radius of 52 m, based on the global two-layer soil model (Table 2). The two-layer model from the P&C data resulted in an equivalent resistivity of 1400 Ω.m for the estimated station radius of 52 m. Based on the average of the two values, an equivalent resistivity of 1000 Ω.m was used in calculating the station ground resistance.

A sub-surface layer resistivity of 1800 Ω.m, as explained in section 2.3, was used in calculating the station touch and step voltages.

For calculating the impedances of the skywire and distribution neutrals, a resistivity of 250 Ω.m for the region was obtained from the Provisional Conductivity Map for Southern Ontario.

3.2 Isolated Station Ground Resistance, R_g

An isolated station ground resistance R_g of 5.2 Ω was calculated using equation 3.3 of the Grounding Guide /1/, based on an estimated equivalent station radius of 52 m for a grid area of 8500 m^2 and 2300 m of buried grid conductors. The grid data were estimated from the station design drawing.

3.3 Skywire Impedance, Z_c

For the two 37 mm^2 (7 #10) alumoweld skywires of the HV double circuit line, the earth return self impedance and the mutual impedance to phase conductors were calculated as 1.49/31 Ω/km and 0.35/80 Ω/km, respectively, using simplified formulas for Carson's earth return impedances. A tower footing resistance of 6.0 Ω was estimated for each tower, based on four augured footings with a footing radius of 0.75 m, a length of 6.7 m and a footing spacing of 15 m. From the ladder network of the skywire self impedance and the tower footing resistance, the conductive chain impedance Z_c of the skywires was calculated as 1.27/16 Ω for an average span length of 180 m near the station.

3.4 Distribution Neutral Impedance, Z_n

The six 27.6-kV feeders are assumed to be grouped in three directions with two circuits in each direction, installed in double circuit duct bank inside the station and carried on double circuit poles outside. The cable sheaths/concentric neutrals are grounded only at the poles and separate 107 mm^2 (AWG 4/0) PVC jacketed copper conductors connect the 170 mm^2 (336 mcm) aerial distribution neutrals to the station grid. The Carson's earth return impedances for the underground and overhead parts of a double circuit neutral were calculated separately and combined together to obtain the total impedance in any one direction. For feeders in each duct bank, a neutral impedance of 0.27/81 Ω was calculated for a circuit distance of 300 m based on two 107 mm^2 (AWG 4/0) copper neutral conductors spaced at approximately 150 mm. For each pole line, a neutral impedance of 0.59/63 Ω was calculated based on the neutral conductor of size of 170 mm^2 (336 mcm) aluminum and assuming distribution taps at 400 m spacings. The neutral is assumed to be grounded at each distribution transformer tap. An equivalent ground resistance of 10 Ω due to water connections at 20 m spacings was assumed for each service drop. The ground rod resistance at distribution transformers was neglected since it is normally large compared to the neutral impedance of a service drop.

For the six distribution feeders, a net neutral impedance Z_n of 0.28/68 Ω was calculated based on the parallel combination of the feeder neutrals in three directions.

3.5 Conductive Equivalent Circuit

Figure 3 shows the conductive equivalent circuit for the grounding system interconnections at the station with respect to fault current distribution. The interconnected station ground impedance was calculated as 0.24/57 Ω, based on the parallel combination of the circuit impedances.

3.6 Tolerable Limits of Touch and Step Voltages

The tolerable limits of touch and step voltages were calculated using equations 2.4 and 2.2 of the Grounding Guide /1/. The calculated touch and step voltage limits are 698 V and 2362 V respectively, based on 150 mm of crushed stone layer at the station and assuming a resistivity of 3000 Ω.m for the crushed stone.

3.7 Modelled Results for a HV Station Fault

For a HV station fault, only the conductive component of the fault current enters the station grounding system due to the shielding of the skywires. This conductive component of the fault current I_f was calculated as SI_f, where S is the shielding factor calculated from the skywire self and mutual impedances. The inductive component of the skywire current is $(1-S)I_f$. The calculated shielding factor is 0.864/-12.

The conductive equivalent circuit in Figure 3 was solved for an injected fault current of S x 1.00/0 A. The station ground potential rise was calculated as $I_g R_g$, where I_g is the ground current split and R_g is the isolated station ground resistance.

The station mesh and step voltages were calculated using equations 70 and 73 respectively of IEEE Guide 80 /3/. Assuming that the station fence is isolated from the station main ground grid as indicated in the design drawing, the fence outside touch voltage was calculated using equation 3.11 of the Grounding Guide /1/. For a HV fault current of 1.00/0 A, the calculated current splits, station ground potential rise and touch and step voltages are given below. Note that the skywire split is the sum of the conductive and the inductive components.

Station ground current split	-	0.04/46 A
Skywire current split	-	0.39/41 A
Distr. neutral current split	-	0.73/-23 A
Station ground potential rise	-	206.9/46 mV
Station mesh voltage	-	63.1/46 mV
Station step voltage	-	27.9/46 mV
Fence outside touch voltage	-	13.8/46 m

Based on these results, for an ultimate HV station ground fault current of 8.5 kA as provided by System Planning Division, the station ground potential rise would be 1.8 kV, the station mesh and step voltages would be 536 V and 237 V respectively, and the fence outside touch voltage would be 117 V.

3.8 Modelled Results for a LV Fault

System Planning Division provided a maximum ground fault current of 18.5 kA for a LV fault at the station bus. However, a LV ground fault at the station will not cause any ground potential rise as the fault current circulates within the station without entering the ground due to the grounded transformer LV neutral.

For a fault outside the station, the maximum fault current will be limited by the source impedance, the impedance of the phase conductor and the ground impedance at the fault location. Simplified calculations were performed to estimate the station grounding system performance in the event of a line-to-ground fault on a feeder outside the station. The entire fault current was assumed to be supplied from the station via the faulted feeder. The estimated fault current in the event of a phase-to-ground fault at a manhole outside the station is 14.5 kA. The fault current would be further reduced to approximately 10 kA for a line-to-ground fault at a first pole outside the station due to the added impedance of the aerial feeder neutral.

The conductive component of the fault current entering the station grounding system was found to be considerably reduced due to the effective shielding of the feeder neutral. The estimated shielding factors for the underground and the overhead feeder neutrals are 17% and 46% respectively. Assuming that the entire fault current returns through the station ground, the skywires and the feeder neutrals, the estimated station ground current split is 0.7% for a fault at the manhole or at a first pole outside the station. The station ground current split would be increased to approximately 1.7% for a fault at a pole in the first span due to a change in the shielding of the faulted circuit.

Based on these results, the maximum estimated station ground potential rise is 90 mV/A for a LV fault at a pole in the first span which would be 900 V for an estimated fault current of 10 kA.

4.0 Discussion of Results

4.1 The generally high measured soil resistivity at the station is consistent with the geology at the site which is reported to be a gravel bed with high water table. The measurements (Table 1) apparently indicate a complex multi-layer soil structure probably with four layers. The non-uniform test results for the same survey locations may be due to the site conditions at the time of the tests. The measured low resistivities at larger probe spacings may be due to water table or due to nearby fences or other metallic objects.

4.2 The apparent resistivities measured at low probe spacings generally agree with the previous measurements by P&C in 1987 at the site /2/. At larger probe spacings the previous measurements resulted in higher values compared to the present measured results probably due to the site conditions at the time of the tests and/or due to the performance of the different instruments used in the two tests. A Megger DET-2 tester was used in the present tests and a Gossen GEOM-3 was used by P&C in 1987 tests.

4.3 Simplified calculations indicated that the ground resistance at Cambridge Preston TS has very little influence in reducing the overall station ground impedance mainly due to the multi-grounded LV distribution system at the station. Calculations indicated that a 200% increase in the station ground resistance would results in an increase of only about 3% in the station ground potential rise. Furthermore, the station ground potential rise for an ultimate fault current of 8.5 kA at the station is well below the safe limit of 3 kV. Therefore, a simple average-fitted two-layer soil model based on a conservative interpretation of the data was considered adequate for calculating the station ground resistance.

4.4 The multi-grounded distribution system is the most significant factor in reducing the interconnected station ground impedance to 0.24 Ω. The calculated station ground resistance is 5.2 Ω.

4.5 The distribution neutrals carry approximately 85% of the HV fault current entering the station grounding system. Also due to the low impedance and the effective shielding of the skywires only about 4% of the total fault current enters the station ground. As a result the station ground potential rise is considerably reduced and is well under the recommended limit of 3 kV for an ultimate HV fault current of 8.5 kA.

4.6 For a HV fault current of 8.5 kA, the touch and step voltages at the station calculated for a maximum measured sub-surface resistivity of 2100 Ω.m were found to be within the permissible limits. However, assuming a conservative value of 3000 Ω.m for crushed stone /1/, the station touch (mesh) voltage was found to exceed the limit of 698 V by approximately 15%.

4.7 For a LV fault, the maximum estimated station ground potential rise of 90 mV/A (900 V for an estimated fault current of 10 kA) is considerably lower than the calculated value of approximately 207 mV/A for a HV station fault (1.8 kV for a fault current of 8.5 kA). Therefore, a detailed study of the station grounding system performance in the event of a LV fault was not considered necessary at this time.

4.8 A previous grounding system study for Cambridge Preston TS was performed in 1987 by the Telecommunication Department for design purposes /4/. This study resulted in an estimated station ground potential rise of 3.2 kV for a HV station fault current of 5.2 kA. This is approximately 615 mV/A and is considerably higher than the 207 mV/A from the present study. The station was under preliminary design stage at the time of the previous study and therefore, the calculations were based on many conservative assumptions, particularly in the area of LV distribution neutrals, as discussed below.

- The previous study is based on distribution neutrals with 30 Ω grounds at quarter mile spacings. The secondary feeder neutrals with water pipe connections to customers appear to be neglected in the study resulting in a high ladder impedance for the distribution neutrals.

- A high tower footing resistance (20 Ω) and a long span length (260 m) assumed in the previous study resulted in a higher estimated skywire chain impedance than the present calculated value.

- Most conservative design resistivities used in the previous calculations yielded a high station ground resistance. However the effect of this on the station ground potential rise should not be very significant as discussed in section 4.3 above.

5.0 CONCLUSIONS

5.1 The soil resistivity measurements at the station indicated a complex multi-layer soil structure with more than two layers. The high measured soil resistivities are consistent with the geology at the site which is reported to be an abandoned gravel pit.

5.2 The station ground resistance was found to have very little influence in reducing the overall station ground impedance. Therefore, a simple two-layer soil model based on a conservative interpretation of the measured soil resistivity data was considered adequate for estimating the station ground resistance. Thus, a two-layer model was approximately fitted to the data points and yielded an upper layer of 350 Ω.m at a depth of 10 m and a bottom layer of 2100 Ω.m.

An equivalent soil resistivity of 1000 Ω.m for an estimated station radius of 52 m was derived from the two-layer soil model for estimating the station ground resistance. A sub-surface layer resistivity of 1800 Ω.m was derived from the measurements for calculating the touch and step voltages.

5.3 The isolated station ground resistance calculated from the grid geometry is 5.2 Ω. The modelled interconnected station ground impedance is 0.24/57 Ω, mainly due to the several multi-grounded distribution neutrals.

5.4 For stations with extensive multi-grounded LV distribution feeders, the distribution neutrals are usually more important than the station ground resistance in deriving the station ground current split.

5.5 In the event of a HV ground fault at the station, 86% of the fault current was found to enter the station grounding system due to the shielding of the skywires. Only about 4% of the fault current enters the station ground due to the low impedances of the distribution neutrals and the skywires.

5.6 The modelled station ground potential rise in the event of a HV fault at the station is 206.9/46 mV/A which would be approximately 1.8 kV for an ultimate fault current of 8.5 kA. This is well under the recommended limit of 3 kV.

5.7 For the above fault current of 8.5 kA, the modelled station mesh and step voltages are 536 V and 237 V respectively and the station fence touch voltage to the public outside is 117 V. These are within the tolerable touch and step voltage limits of 698 V and 2362 V respectively, calculated for the station.

5.8 Simplified models were developed to estimate the maximum station ground potential rise in the event of a LV ground fault. The maximum estimated station ground potential rise is 90 mV/A for a fault on a pole on the first span which would be 900 V for an estimated fault current of 10 kA. This is considerably lower than the modelled value of 1.8 kV for a HV station fault and therefore, a detailed study of the station grounding system performance in the event of a LV fault was not considered necessary at this time.

6.0 ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation and contribution from Cambridge Hydro Electric Commission, District P&C, Central Region Marketing, Design and Development Division-Transmission and System Planning in conducting the study.

Approved:

M Edgar
for
A.F. Baljet
Manager
Electrical Research Department

Submitted:

R.P. Pillai
Engineer
System Studies Section

RPP:am

REFERENCES

1. Ontario Hydro, Grounding Guide, 1982 Edition.

2. Soil resistivity test data attached to memo dated May 13, 1987, File #440-Cambridge Preston, from Mr. J.A. Barnstigin, P&C, Kitchener District, addressed to Mr. R.C. Tse, Stations Programs Department.

3. IEEE standard 80, IEEE Guide for Safety in AC Substation Grounding, 1986 Revision.

4. Cambridge Preston GPR Study Report attached to memo dated July 6, 1987 from Mr. R.G. Irvine addressed to Mr. F. Dudzik, Telecommunication Department.

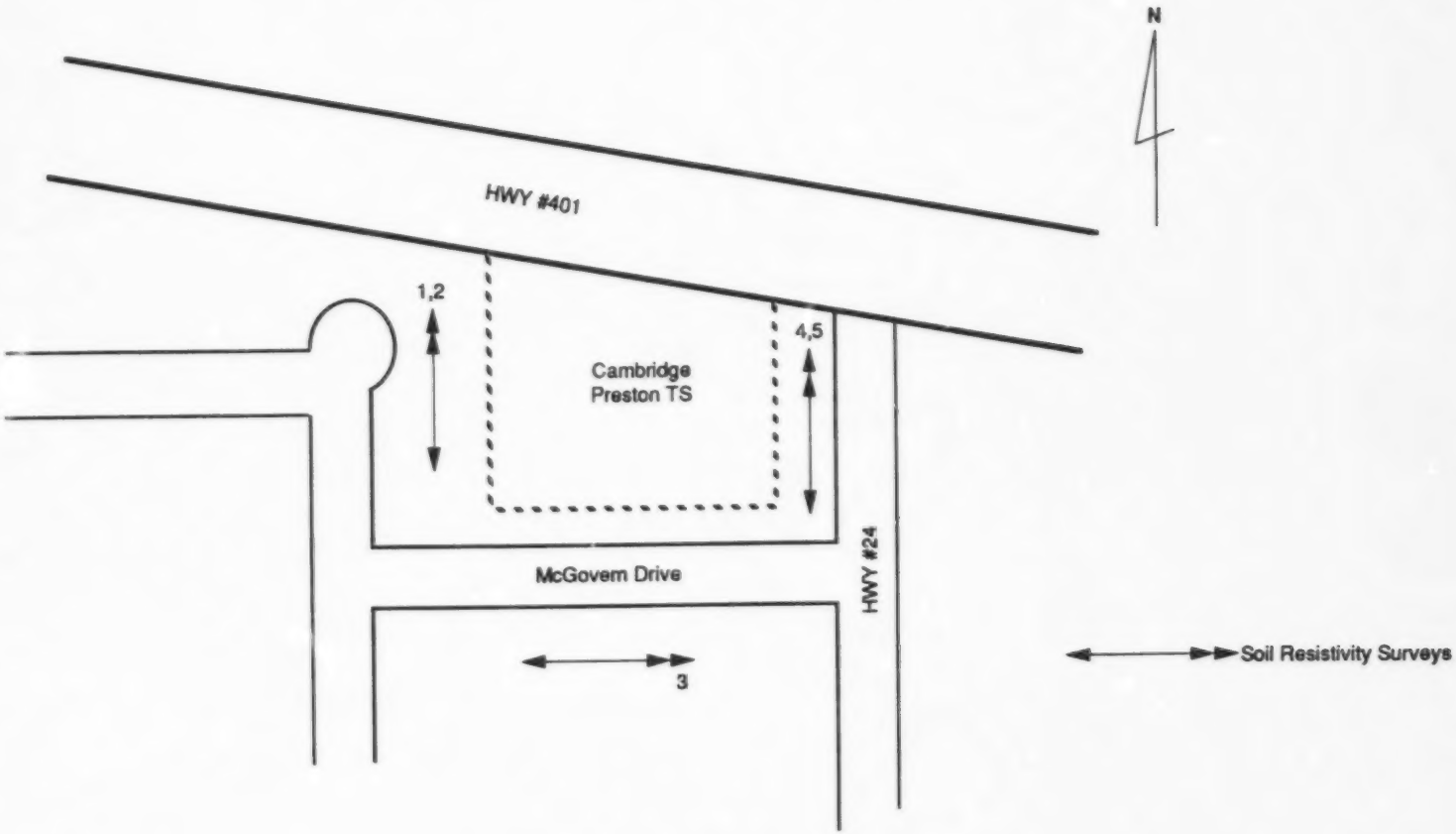

FIGURE 1
CAMBRIDGE PRESTON TS
LAYOUT WITH RESPECT TO SOIL RESISTIVITY SURVEYS

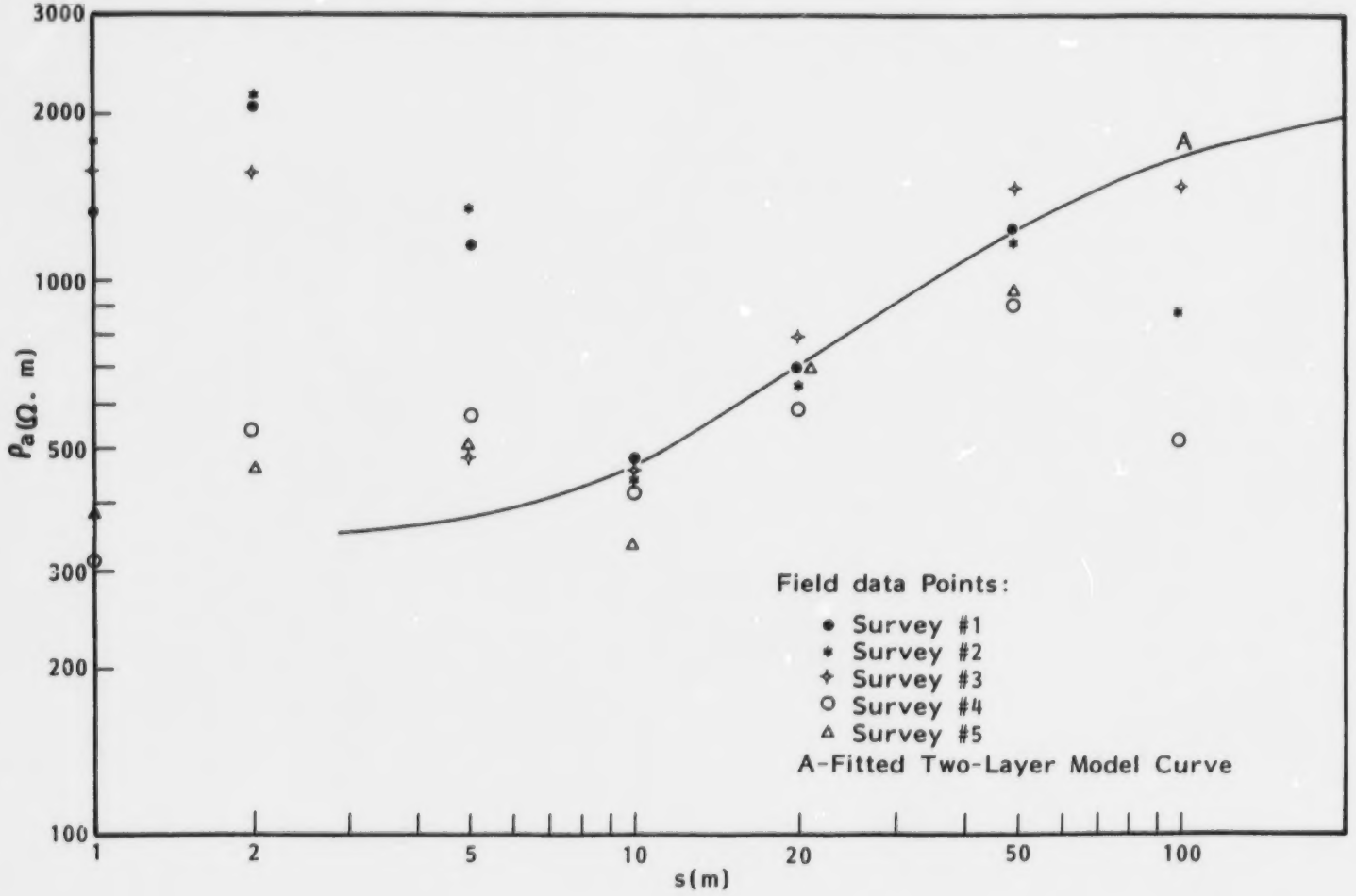

FIGURE 2

CAMBRIDGE PRESTON TS
MEASURED APPARENT SOIL RESISTIVIES AND FITTED MODEL CURVE

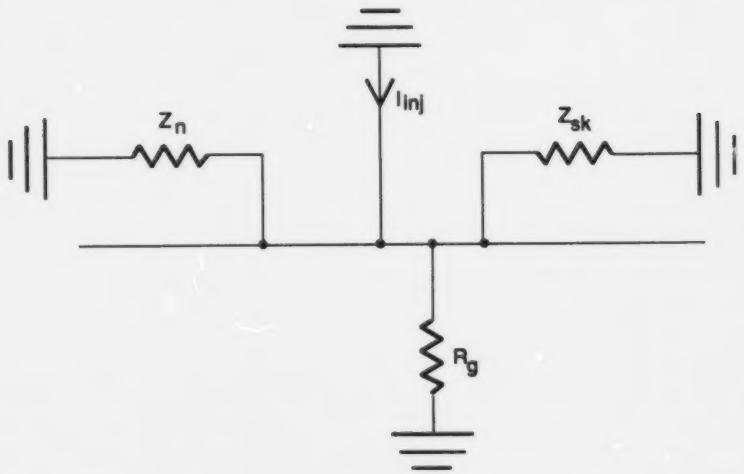

FIGURE 3
CAMBRIDGE PRESTON TS
CONDUCTIVE EQUIVALENT CIRCUIT

APPENDIX A

SUMMARY OF FORMULAS USED IN GROUNDING CALCULATIONS

1. Conductor Earth Return Self Impedance, Z_s

$$Z_s = R_s + jX_s \quad (\Omega/km) \tag{1}$$

$$R_s = 0.059 + R_{ac} \quad (\Omega/km) \tag{2}$$

$$X_s = 0.0377 \ln (8440 \rho_s / GMR^2) \tag{3}$$

Where, R_{ac} = conductor ac resistance (Ω/km)
ρ_s = soil resistivity (Ω.m)
GMR = conductor geometric mean radius (m)

For pipes or shields, R_{ac} and X_{ac} (conductor internal reactance added to X_s) are calculated as shown in Ontario Hydro Research report No. 83-433-K, dated November 7, 1983, by E.P. Dick.

2. Conductor Earth Return Mutual Impedance, Z_m

$$Z_m = R_m + jX_m \quad (\Omega/km) \tag{4}$$

$$R_m = 0.0377 \tan^{-1} (8440 \rho_s / GMD^2) \tag{5}$$

$$X_m = 0.0377 \ln [(8440 \rho_s / GMD^2) + 1] \quad (\Omega/km) \tag{6}$$

Where, ρ_s = soil resistivity (Ω.m)
GMD = geometric mean diastance between conductors (m)

3. Tower Footing Resistance, R_t

3.1 Square Footing

$$R_t = \rho_s /2\pi [(1/a) + (2.707/w)] \quad (\Omega) \tag{7}$$

Where, ρ_s = soil resistivity (Ω.m)
a = footing radius (m)
w = footing spacing (m)

3.2 Single Augured Footing

$$R_t = [\rho_s / (2 \pi L)] [\ln (2 L/a)] \quad (\Omega) \qquad (8)$$

Where, ρ_s = soil resistivity (Ω.m)
L = footing length (m)
a = footing radius (m)

3.3 Four Augured Footing

$$R_t = 0.25 (R_s + R_{m1} + R_{m2} + R_{m3}) \qquad (9)$$

Where, R_s = footing self resistance from equation (8)
R_{m1}, R_{m2}, R_{m3} = mutual resistances to other footings from equation (10)

$$R_m = [\rho_s / (2 \pi L)] [\ln \{(L/x) + SQRT(1+(L^2/x^{2}))\}] \quad (\Omega) \qquad (10)$$

Where, L = footing legth (m)
x = distance to the other footings in turn (m)

4. Chain Impedance of Skywires, Z_c

$$Z_c = Z_s \, l \, R_t \quad (\Omega) \qquad (11)$$

Where, Z_s = conductor earth return self impedance (Ω/km)
l = span length (km)
R_t = tower footing resistance (Ω)

5. Shielding Factor, S

$$S = 1 - (Z_m / Z_s) \qquad (12)$$

Where, Z_m = conductor earth return mutual impedance (Ω/km)
Z_s = conductor earth return self impedance (Ω/km)